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Measurement of the Bottom Baryon Resonances Σ_b and Σ_b^*

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Abstract

In this note we present a measurement of the masses and widths of the four states $\Sigma_b^{(*)\pm}$ in decays to $\Lambda_b^0\pi^\pm$.

This analysis analysis is based on a data sample corresponding to an integrated luminosity of $\int\mathcal{L}\,dt \approx 6.0\,\mathrm{fb}^{-1}$. We measure the four $\Lambda_b^0\pi^\pm$ resonant states masses to be:

$$\begin{aligned}
m(\Sigma_b^+) &= 5811.2^{0.9}_{-0.8}\,(\mathrm{stat}) \pm 1.7\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
m(\Sigma_b^-) &= 5815.5^{+0.6}_{-0.5}\,(\mathrm{stat}) \pm 1.7\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
m(\Sigma_b^{*+}) &= 5832.0 \pm 0.7\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
m(\Sigma_b^{*-}) &= 5835.0 \pm 0.6\,(\mathrm{stat}) \pm 1.8\,(\mathrm{syst})\,\mathrm{MeV}/c^2
\end{aligned}$$

We report the first measurement of isospin mass splittings for the $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ isospin multiplets of $\Sigma_b^{(*)}$ bottom baryons to be:

$$\begin{aligned}
m(\Sigma_b^+) - m(\Sigma_b^-) &= -4.2^{+1.1}_{-0.9}\,(\mathrm{stat})^{+0.07}_{-0.09}\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
m(\Sigma_b^{*+}) - m(\Sigma_b^{*-}) &= -3.0 \pm 0.9\,(\mathrm{stat})^{+0.12}_{-0.13}\,(\mathrm{syst})\,\mathrm{MeV}/c^2
\end{aligned}$$

We also report the first measurement of the widths of these states:

$$\begin{aligned}
\Gamma(\Sigma_b^+) &= 9.2^{+3.8}_{-2.9}\,(\mathrm{stat})^{+1.0}_{-1.1}\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
\Gamma(\Sigma_b^-) &= 4.3^{+3.1}_{-2.1}\,(\mathrm{stat})^{+1.0}_{-1.1}\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
\Gamma(\Sigma_b^{*+}) &= 10.4^{+2.7}_{-2.2}\,(\mathrm{stat})^{+0.8}_{-1.2}\,(\mathrm{syst})\,\mathrm{MeV}/c^2 \\
\Gamma(\Sigma_b^{*-}) &= 6.4^{+2.2}_{-1.8}\,(\mathrm{stat})^{+0.7}_{-1.1}\,(\mathrm{syst})\,\mathrm{MeV}/c^2
\end{aligned}$$

I. INTRODUCTION

The Standard Model predicts the existence of the Λ_b^0 baryon, a singlet with quark content $b[ud]$ and ground state $J^P = \frac{1}{2}^+$, and two states Σ_b, Σ_b^*, which are isospin triplets with quark content $b\{q_1q_2\}$ and ground states with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$ respectively. These states can decay to the singlet Λ_b^0 via strong processes involving pion emissions provided sufficient phase space is available for a given mode. According to the established nomenclature, Σ_b, Σ_b^* are resonance states. The phenomenological framework has been developed within The Heavy Quark Symmetry (see [1–4]) picture of heavy hadrons, please see also [5, 6]. The recent developments in phenomenological approaches and numerical expectations can be found in [7–15].

In this note, we present measurements of the masses and widths of the $\Sigma_b^{(*)\pm}$ four states[1] in the exclusively reconstructed modes $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$, and $\Lambda_c^+ \to pK^-\pi^+$

These states were discovered by CDF on 2006 [17].

II. CDF DETECTOR AND TRIGGER

The component of the CDF detector [18] most relevant for this analysis is the tracking system. The tracking system lies within a uniform axial magnetic field of strength 1.4 T. The inner tracking volume up to a radius of 28 cm is filled with 6–7 layers of double-sided silicon microstrip detectors, the *Silicon Vertex Detector* (SVX II), and the *Intermediate Silicon Layers* (ISL) [19]. An additional layer of single-sided silicon, the *Layer00* (L00) [19], is mounted directly to the beam-pipe at a radius of 1.5 cm, providing an excellent resolution of the *impact parameter* d_0, defined as the distance of closest approach of the track to the interaction point in the transverse plane. The remainder of the tracking volume up to the radius of 137 cm is occupied with an open-cell drift chamber (COT) [20].

A three-level trigger system is used for the online event selection. The trigger components important for this analysis are the extremely fast tracker (XFT) [21], which, at level 1 of the trigger system, groups COT *hits* into tracks in the transverse plane. We refer as *silicon hit* to a cluster of strips activated due to the cross of a charged particle.

The events are selected by the *Two Track Trigger* (TTT), which selects events that contain track pairs with transverse momentum larger that 2 GeV/c and $120\,\mu\text{m} < d_0 < 1\,\text{mm}$. These tracks are refered to as "SVT tracks". This trigger ensures an enriched sample on B hadron decays.

III. DATA SAMPLE & EVENT SELECTION

This analysis is based on an integrated luminosity of 6.0 fb^{-1} collected with the CDF detector between March 2002 and February 2010. The data are collected using the TTT.

The analysis begins with the reconstruction of the $\Lambda_c^+ \to pK^-\pi^+$ decay by fitting three tracks to a common vertex. Then, the $\Lambda_b^0 \to \Lambda_c^+\pi_b^-$ decay is reconstructed by one mass constraint fit of the Λ_c^+ candidate with one track. At this stage is required that two of the four tracks (p, K, π^-, π_b) correspond with the two SVT tracks.

Finally, the Λ_b^0 candidate is combined with a track by a one vertex-track fit to build the $\Sigma_b^{(*)}$ candidate. The analysis is performed on the Q-value, $Q = m(\Lambda_b^0\pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$ because the Λ_b^0 resolution is canceled by taking the difference.

A. Optimization

From [17] the main background source is the combination of real Λ_b^0 with random tracks produced during the hadronization and the underline event. In addition, CDF has the largest sample of fully reconstructed with hadronic mode Λ_b^0 baryons. These two facts motivate to perform an optimization procedure based on experimental data only where our aim is to optimize our data sample in order to have as much Λ_b^0 as possible.

Table I summarizes the analysis cuts after the optimization. Figure 1 shows the Λ_b^0 signal after applying the optimized cuts.

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[1] Unless otherwise stated all references to the specific charge combination imply the charge conjugate combination as well.

B. Significance

The significance of the observed signals is tested against several null hypothesis using the log-ratio of the minimal likelihoods, $\mathcal{L}_1/\mathcal{L}_0$, reached by the fitter for our base line fit model hypothesis, –log $\mathcal{L}_1$ and for a particular null hypothesis, –log $\mathcal{L}_{\prime}$ our default base line one is going to be tested against.

$$-2 \cdot log\frac{\mathcal{L}_0}{\mathcal{L}_1} = -2 \cdot \Delta(log\mathcal{L}) \tag{1}$$

We interpret Eq. 1 as a χ^2 of the null hypothesis spectrum to fluctuate to our base signal one with a number of degrees of freedom equal to the difference in the number of floating parameters between both hypotheses. We consider the next null hypotheses to test the combined pair or individual one of observed charged states of $\Sigma_b^{(*)\pm}$

- Any single peak instead of the two ones is observed.
- The signal Σ_b^* is observed but the Σ_b has been missed. We impose a loose requirement on an existence of the second peak, Σ_b^*, viz. we fix the width of Σ_b^* to the expected theoretical value of $12\,\mathrm{MeV}/c^2$ but let the fitter to find and fit the Σ_b^* position which is again floating, within $Q_0 \in (0.003, 0.210)\,\mathrm{GeV}/c^2$.
- The signal Σ_b is observed but the Σ_b^* has been missed. We impose a loose requirement on an existence of the first peak, Σ_b, viz. we fix the width of Σ_b to the expected theoretical value of $7\,\mathrm{MeV}/c^2$ but let the fitter to find and fit the Σ_b position which is again floating, within $Q_0 \in (0.003, 0.210)\,\mathrm{GeV}/c^2$.
- Any single peak is observed, the null hypotheses is our base line background model.
- No both Σ_b and Σ_b^* are observed.

Tables II and III summarize the results of these tests. For every null hypothesis tested the significance is above $7.0\,\sigma$ in Gaussian terms.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in this analysis come from three sources:

- Fit procedure: there is an small systematic uncertainty on the width measurements introduced by the fitter. We conservatively assign a systematic error based on the results of performing many pseudo-experiments.
- Uncertainty on the momentum scale.
- Assumptions made about the fitter. These include the following:
  - Fixed parameters on the fitter describing the resolution of the detector. This is the dominant contribution to the total systematic uncertainty on the width measurements.
  - The model describing the background.

The effect on the Σ_b Q-values of the uncertainty on the momentum scale is estimated by comparing the differences in the Q-values between CDF and the *Particle Data Group* (PDG) [22] for several other low-enery resonances ($\Sigma_c^{++} \to \Lambda_c^+\pi^+$, $\Sigma_c^0 \to \Lambda_c^+\pi^-$, $\Lambda_c^{*+} \to \Lambda_c^+\pi^+\pi^-$ and $D^{*\pm} \to D^0\pi^\pm$). Those differences are fitted as a function of the Q-value, to a linear fit. For every $\Sigma_b^{(*)}$ state, we estimate a systematic error evaluating this linear fit at the Q-value of the $\Sigma_b^{(*)}$ state.

The effect on the Σ_b widths of the uncertainty on the momentum scale is estimated by fitting the D^*–D^0 mass difference distribution in different ranges of the softpion transverse momentum. All the returned widths for those fits are lower than 0.2 MeV/c^2, so we conservatively assign this value as the systematic error on the widths.

There are systematic uncertainties due to several assumptions made on the fitter. We extract the parameters describing the Σ_b resolution from Monte Carlo simulation, and we keep fixed those parameters in our fitter. For every fixed parameter in the fitter, we estimate systematics errors generating pseudo-experiments with those parameters describing the resolution detector being varied. We then fit these samples with both, our default fitter and the fitter

	Cut Quantity	value
p, K, $\pi^{\pm}$ from $\Lambda_b^0 \rightarrow \Lambda_c^+\pi_b^-$ $\Lambda_c^+ \rightarrow pK^-\pi^+$	N(r–ϕ) SVX II hits	≥ 3
	N(COT–stereo) hits	≥ 10
	N(COT–axial) hits	≥ 10
	$\lvert d_0 \rvert$	$< 0.1\,\mathrm{cm}$
	p_T	$> 400\,\mathrm{MeV}/c$
$\Lambda_b^0 \rightarrow \Lambda_c^+\pi_b^-$	$c\tau(\Lambda_b^0)$	$> 200\,\mu\mathrm{m}$
	$c\tau(\Lambda_b^0)/\sigma_{c\tau}$	> 12.0
	$\lvert d_0(\Lambda_b^0) \rvert$	$< 80\,\mu\mathrm{m}$
	$c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$> -150\,\mu\mathrm{m}$
	$c\tau(\Lambda_c^+ \leftarrow \Lambda_b^0)$	$< 250\,\mu\mathrm{m}$
	$p_T(\pi_b^-)$	$> 1.5\,\mathrm{GeV}/c$
	$p_T(\Lambda_b^0)$	$> 4.0\,\mathrm{GeV}/c$
	$\lvert m(\Lambda_c^+\pi^-) - m(\Lambda_b^0) \rvert$	$< 3 \cdot 19.22\,\mathrm{MeV}/c^2$, $\pm 3\sigma$ m(Λ_b^0) = 5619.15 MeV/c^2
	Prob(χ^2_{3D}) of Λ_b^0 vertex fit	> 0.0001
$\Sigma_b^{*\pm} \rightarrow \Lambda_b^0\pi^{\pm}_{soft}$	$p_T(\Sigma_b^{(*)})$	$> 4.0\,\mathrm{GeV}/c$
	$\lvert d_0/\sigma_{d_0} \rvert(\pi_{soft})$	< 3.0
	$p_T(\pi_{soft})$	$> 0.2\,\mathrm{GeV}/c$
	$p_T(\pi_{soft})$	$< p_T(\pi_b^-)$

TABLE I: Final selection cuts after optimization. The first three rows refers to the minimum number of silicon hits required in the tracks.

with varied parameters. For every parameter, the systematic error is estimated as the mean of a gaussian fit to the distribution of the differences in the returned values by the two fitters for this parameter.

We estimate the systematic uncertainty on every parameter comming from our particular election of the background model using simulation. We generate many pseudo-experiments using an alternative background model. Then we fit these samples with our default fitter and the one with the alternative background model. For every parameter, we build the two distributions with the differences between the generated and fitted values. We fit both with a gaussian distribution and take the difference between the gaussian means returned by the fitters. This difference plus its error is our estimation of the uncertainty

The systematic uncertainties are summarized in the Table IV.

V. RESULTS

From the measured Σ_b Q-values we extract the absolute masses using the PDG value of the $\pi^{\pm}$ mass and the best CDF mass measurement for Λ_b^0, which is $m(\Lambda_b^0) = 5619.7 \pm 1.2\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst})$ MeV/c^2 [23]. The addition in quadrature of the Λ_b^0 statistical and systematical uncertainties is added to the systematic error of the absolute masses.

Also, from these Q-values it is straightforward to extract the isotopic mass differences between oppositely charged states within the two isotriplets $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$. For these differences, the quoted statistical errors are the corresponding Q-values statistical errors added in quadrature. To quote the systematic error, we added in quadrature the uncertainty due to the assumed background. The other uncertainty sources are correlated, so we added in quadrature their differences.

Table V summarizes the results.

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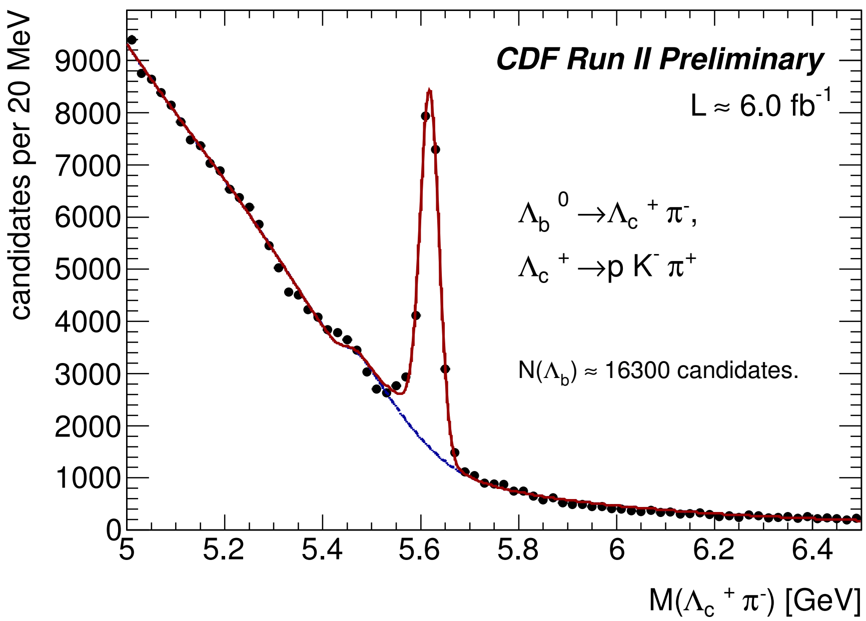

FIG. 1: Λ_b^0 signal reconstructed using the total statistics of Periods 0 − 28.

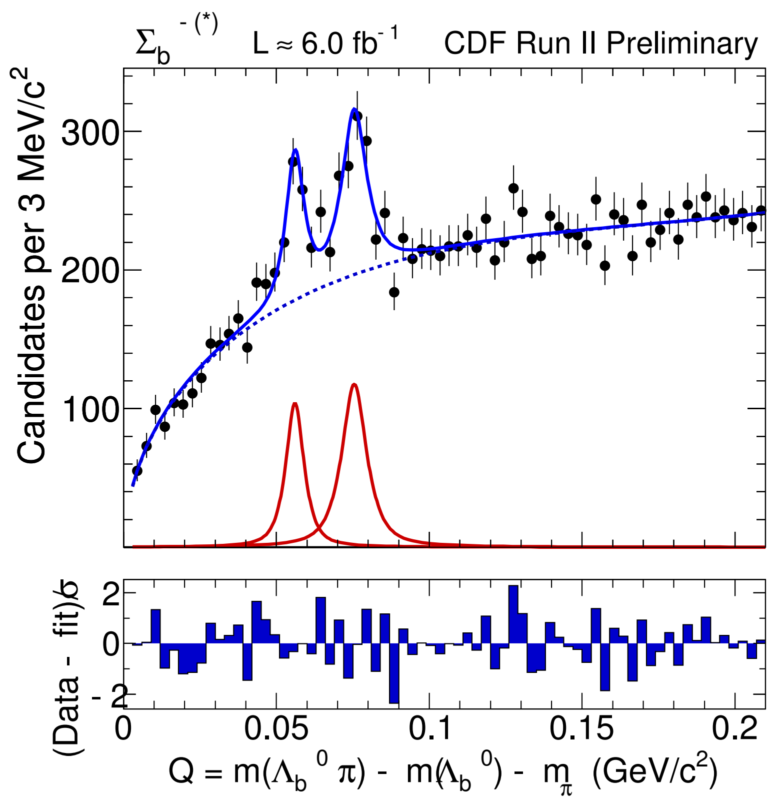

FIG. 2: $\Sigma_b^{(*)-}$ candidates: the Q-value spectrum, where $Q = M(\Lambda_b^0\pi^-) - M(\Lambda_b^0) - m_\pi$, with the unbinned fit profile superimposed. The spectacular double peak structure is seen on the plot.

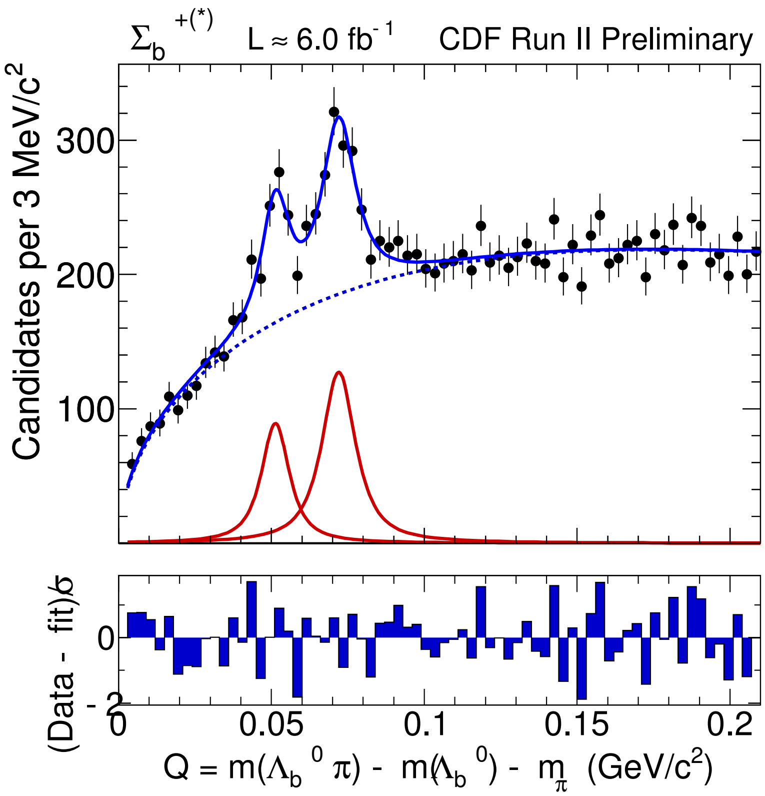

FIG. 3: $\Sigma_b^{(*)+}$ candidates: the Q-value spectrum, where $Q = M(\Lambda_b^0\pi^+) - M(\Lambda_b^0) - m_\pi$, with the unbinned fit profile superimposed. The spectacular double peak structure is seen on the plot.

Null Hypo.	$-2 \cdot \Delta(log\mathcal{L})$	ΔNDF	Prob(χ^2)	N_σ	Comment
Any single peak	$-2 \cdot (-32)$	3	$\approx 8.2 \cdot 10^{-14}$	7.5	w.r.t. double pk.
No Σ_b^-, with Σ_b^{*-}	$-2 \cdot (-35)$	4	$\approx 2.3 \cdot 10^{-14}$	7.6	w.r.t. double pk. $\Gamma_{02} = 12\,\mathrm{MeV}/c^2$
No Σ_b^{*-}, with Σ_b^-	$-2 \cdot (-57)$	4	$\approx 1.0 \cdot 10^{-23}$	10.0	w.r.t. double pk. $\Gamma_{01} = 7\,\mathrm{MeV}/c^2$
No any Signal	$-2 \cdot (-55)$	3	$\approx 1.1 \cdot 10^{-23}$	10.0	w.r.t. single pk.
No any Signal	$-2 \cdot (-87)$	6	$\approx 6.4 \cdot 10^{-35}$	12.3	w.r.t. double pk.

TABLE II: Tests of the baseline $\Sigma_b^{(*)-}$ fit results against several null hypothesis. Robust significance above Gaussian $7.0\,\sigma$.

China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-20002, Probe for New Physics.

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Null Hypo.	$-2\cdot\Delta(log\mathcal{L})$	ΔNDF	Prob(χ^2)	N_σ	Comment
Any single peak	$-2\cdot(-30)$	3	$\approx 5.9\cdot 10^{-13}$	7.2	w.r.t. double pk.
No Σ_b^+, with Σ_b^{*+}	$-2\cdot(-33)$	4	$\approx 1.6\cdot 10^{-13}$	7.4	w.r.t. double pk. $\Gamma_{02} = 12\,\mathrm{MeV}/c^2$
No Σ_b^{*+}, with Σ_b^+	$-2\cdot(-84)$	4	$\approx 2.8\cdot 10^{-35}$	12.4	w.r.t. double pk. $\Gamma_{01} = 7\,\mathrm{MeV}/c^2$
No any Signal	$-2\cdot(-79)$	3	$\approx 4.9\cdot 10^{-34}$	12.2	w.r.t. single pk.
No any Signal	$-2\cdot(-109)$	6	$\approx 2.8\cdot 10^{-44}$	14.0	w.r.t. double pk.

TABLE III: Tests of the baseline $\Sigma_b^{(*)+}$ fit results against several null hypothesis. Robust significance above Gaussian $7.0\,\sigma$.

Signal Parameter	Mass Scale	Fit Procedure	Res.	Back.	Total	%
Σ_b^+ Q, MeV/c^2			0.07	0.05	0.09	0.2
	−0.35		−0.12	−0.05	−0.37	1
Σ_b^+ Γ, MeV/c^2	0.20		0.94	0.40	1.04	11
	−0.20	−0.38	−0.89	−0.40	−1.07	12
Σ_b^+ events			16	9	18	4
			−11	−9	−15	3
Σ_b^- Q, MeV/c^2			0.05	0.04	0.07	0.1
	−0.38		−0.07	−0.04	−0.39	1
Σ_b^- Γ, MeV/c^2	0.20		0.85	0.50	1.01	23
	−0.20	−0.27	−0.87	−0.50	−1.06	25
Σ_b^- events			9	34	35	11
			−8	−34	−35	10
Σ_b^{*+} Q, MeV/c^2			0.06	0.10	0.12	0.2
	−0.52		−0.13	−0.10	−0.55	1
Σ_b^{*+} Γ, MeV/c^2	0.20		0.64	0.50	0.83	8
	−0.20	−0.29	−1.01	−0.50	−1.18	11
Σ_b^{*+} events			7	24	25	3
			−13	−24	−27	4
Σ_b^{*-} Q, MeV/c^2			0.06	0.06	0.08	0.1
	−0.56		−0.08	−0.06	−0.57	1
Σ_b^{*-} Γ, MeV/c^2	0.20		0.65	0.30	0.74	12
	−0.20	−0.23	−0.96	−0.30	−1.05	16
Σ_b^{*-} events			7	28	29	6
			−8	−28	−29	6

TABLE IV: Summary of the systematic errors. For every parameter, the systematic errors associated with the corresponding uncertainty sources are listed in the following order: mass scale, fit procedure, resolution, assumed background. The total systematic error is obtained by adding all the associated errors in quadrature. The last column shows, for every parameter, the % of the total systematic uncertainty with respect the measured value for this parameter.

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State	Q-value	absolute mass	Γ	Yield
Σ_b^+	$52.0^{+0.9}_{-0.8}$ (stat) $^{+0.09}_{-0.4}$ (syst)	$5811.2^{0.9}_{-0.8} \pm 1.7$ (syst)	$9.2^{+3.8}_{-2.9}$ (stat)$^{+1.0}_{-1.1}$ (syst)	468^{+110}_{-95} (stat)$^{+18}_{-15}$ (syst)
Σ_b^-	$56.2^{+0.6}_{-0.5}$ (stat) $^{+0.07}_{-0.4}$ (syst)	$5815.5^{+0.6}_{-0.5} \pm 1.7$ (syst)	$4.3^{+3.1}_{-2.1}$ (stat)$^{+1.0}_{-1.1}$ (syst)	333^{+93}_{-73} (stat) ± 35 (syst)
Σ_b^{*+}	$72.7 \pm 0.7^{+0.12}_{-0.6}$ (syst)	$5832.0 \pm 0.7 \pm 1.8$ (syst)	$10.4^{+2.7}_{-2.2}$ (stat) $^{+0.8}_{-1.2}$ (syst)	782^{+114}_{-103} (stat)$^{+25}_{-27}$ (syst)
Σ_b^{*-}	$75.7 \pm 0.6^{+0.08}_{-0.6}$ (syst)	$5835.0 \pm 0.6 \pm 1.8$ (syst)	$6.4^{+2.2}_{-1.8}$ (stat) $^{+0.7}_{-1.1}$ (syst)	522^{+85}_{-76} (stat) ± 29 (syst)
	Isospin Mass Splitting			
m(Σ_b^+) - m(Σ_b^-)	$-4.2^{+1.1}_{-0.9}$ (stat)$^{+0.07}_{-0.09}$ (syst)			
m(Σ_b^{*+}) - m(Σ_b^{*-})	-3.0 ± 0.9 (stat)$^{+0.12}_{-0.13}$ (syst)			

TABLE V: Summary of the final results. Masses and widths are in MeV/c^2.

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